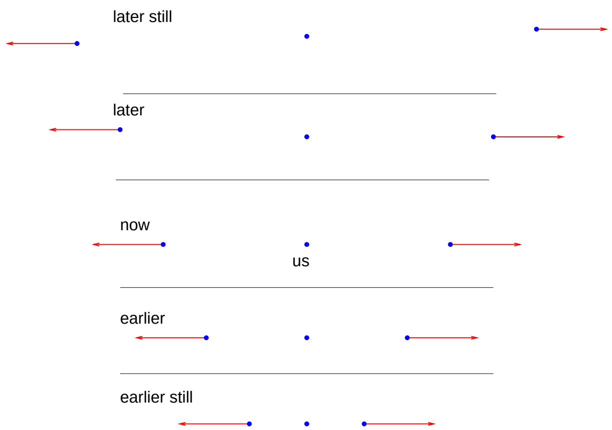
Astro 350
Lecture 27
Oct. 31, 2012

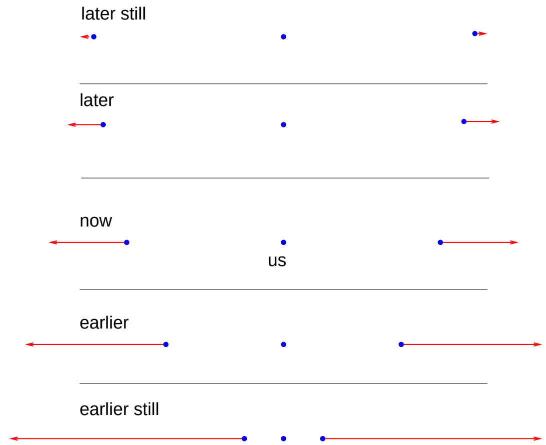
Announcements:
- good news: no HW or discussion this week
- spooky news: Hour Exam 2 on Friday, info online
  Office Hours: instructor–today 2pm
  TA: tomorrow 9:30-10:30 am
- **Discussion 8** up today, due next Wednesday

Last time:
- effect of matter in the universe
  $\rightarrow$ weight is fate! density is destiny! *Q: why?*
  Q: velocity change and fate in "empty" U? why?
  Q: in low-density U? high-density U?
- measuring the *changes* in expansion rate
  Q: expected result in "empty" U? U with matter?
  Q: actual observed result?

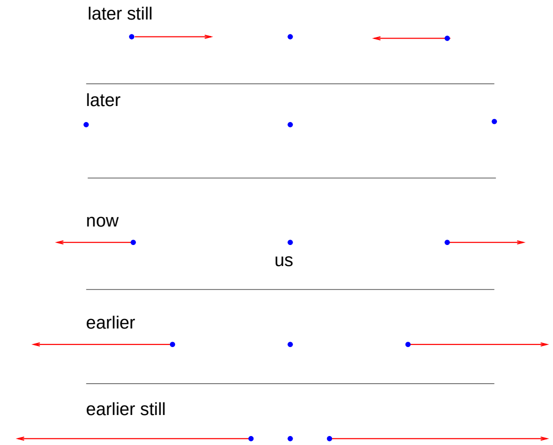
Empty Universe: "Coasting"



Low−matter−density universe: future



High−matter−density universe: future



also last time:
cosmic expansion history and cosmic acceleration

key ideas:

- at any time t, everywhere $v(t) = H(t)\ r(t)$

- when looking at galaxies far, far away
  seeing light emitted a long time ago

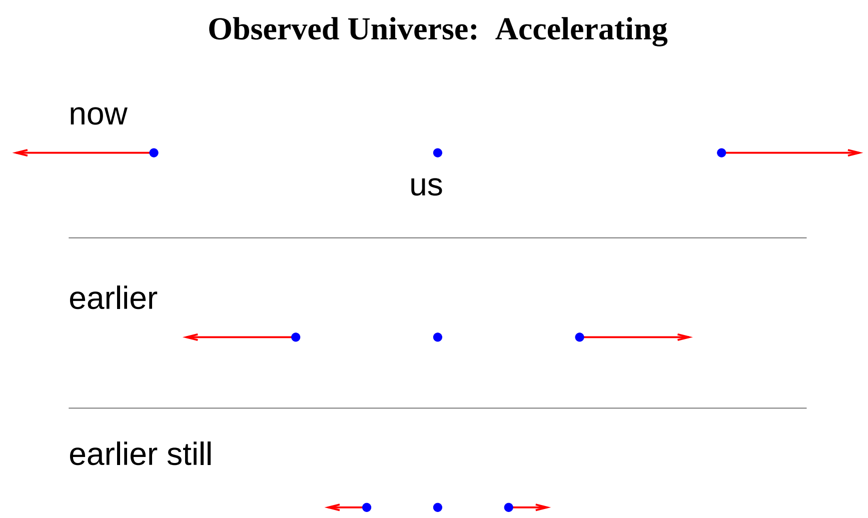
- so if measure v (from redshift) and r (from std candle)
  then can find $H(t) = v(t)/r(t)$ = expansion at past time t!

- even better: can find $H(t)$ for many times t *Q: how?*

Bottom line:
⋆ can measure *change* in expansion rate
$\Rightarrow$ can measure cosmic deceleration/acceleration

Distant Supernovae: The Verdict

Our actual observed universe: galaxies *slower* in past!



SN data: $H(z)$ **smaller** in the past (high z and small t)

$\Rightarrow H(z)$ **increases** with time!

$\Rightarrow \ddot{a} > 0$!

expansion rate: **accelerated!**

Q: what would this mean in the pop fly analogy?

Accelerating Universe: Pop Fly Analogy

Pop fly: ball thrown up in the air
ordinary baseballs: made of matter, feel Earth's gravity
$\rightarrow$ moves ever slower on the way up
$\rightarrow$ decelerated

but the *Universe* does the opposite!
a pop fly acting like the Universe
would get *faster* as it gets higher!
and so would launch itself to space!?!

2011 Nobel Prize in Physics

given to Saul Perlmutter, Brian Schmidt, and Adam Riess

`www: 2011 Nobel Prize`

> for the discovery of the accelerating expansion of the Universe through observations of distant supernovae

Q: why is this Nobel-worthy?

Q: notice what the prize does not *mention?*
that is, what does their work not *tell us?*

Q: what does acceleration (and not deceleration) imply about the gravitational behavior dominating the universe today?

An Accelerating Universe: Implications

Recall: expected deceleration because ordinary matter
(even dark matter!) has gravitational attraction
matter-filled universe should have *slowing* expansion
→ if matter is all there is, U should decelerate

But: found acceleration – exact opposite of intuition
→ something present which has gravitational repulsion!
→ Universe seems to contain something having "antigravity" !?!
...and huge amounts of such stuff!
enough of it to overwhelm the attraction of ordinary matter!

In more detail: SN Ia: $\ddot{a} > 0$, but Friedmann sez

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3\frac{P}{c^2}\right)$$

$\Rightarrow \rho + 3P/c^2 < 0$

$\Rightarrow P < -3\rho c^2$ negative pressure!?!

Physical "interpretation":

recall: $F =$ pressure $\times$ area *diagram: piston,* A, P, F

$P > 0$: outward force (e.g., ideal gas)

$P < 0$: inward force (e.g., elastic)

Cosmic Expansion History: the Full Story

in fact, observations show that cosmic expansion
had *two* phases

⋆ *today and in the recent past*
expansion is **accelerating**
opposite of prediction from matter + General Relativity

⋆ *in the more distant past*
at redshifts $z > 0.3$, times before $t < 10$ billion years
that is, more than about 3 billion years ago
expansion was **decelerating**
agrees with prediction from matter + General Relativity!

Cosmic Acceleration: Who Ordered That?!

ordinary matter and ordinary gravity: **attractive**
gravity acts to draw galaxies together,
$\Rightarrow$ slows outward expansion
should give cosmic **deceleration**

but we observe cosmic **acceleration**!
two known options:

1. Universe contains something bizarre that
pushes objects apart!
in fact, this repulsion has to be so strong
that it overcomes gravity attraction from matter!

2. *Q: what's the other option?*

Einstein Overthrown?

cosmic acceleration seen when looking at the Universe
over vast distances

result is surprising because our gravity theory
= Einstein's General Relativity
predicts gravity makes matter attractive

but note: while GR very well tested on Earth
and in Solar System
not tested on cosmic lengthscales

perhaps acceleration tells us:
General Relativity is incomplete/wrong
$\rightarrow$ if so, need new gravity theory!
Q: requirements for such a theory

Improving on Einstein?

if new gravity theory:
still have to explain *all* data

so: any new theory has to

- give same answers as GR on Earth, solar system scales
- and keep other successful GR features: redshifting, lensing, time dilation
- yet also give different *answers on cosmic scales*

iClicker Poll: The Reason for Cosmic Acceleration

Vote your conscience!

Of these two basic explanations for cosmic acceleration
Which do you think is right?

A General Relativity *correct*, but the Universe contains something bizarre that makes it accelerate

B General Relativity *incorrect*, and the Universe only contains matter

Explaining Cosmic Acceleration

Cosmologists are working hard on *both* avenues

- a new cosmic "accelerant": "dark energy"
- alternatives to General Relativity: "modified gravity"

Hour Exam 2

Sample Questions: Multiple Choice

Special Relativity

Barack and Mitt give speeches from inside spacecrafts moving relative to each other with speed $v = 0.9c$

Barack notices that when his own watch ticks off 10 seconds he observes Mitt's watch ticking off

(a) 10 seconds

(b) $<$ 10 seconds

(c) $>$ 10 seconds

Mitt notices that when his own watch ticks off 10 seconds he observes Barack's watch ticking off

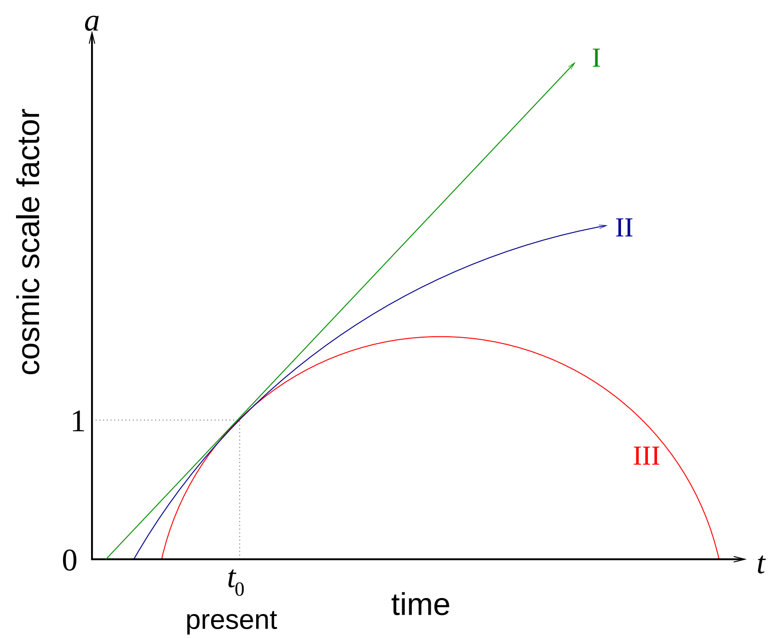
(a) 10 seconds

(b) $<$ 10 seconds

(c) $>$ 10 seconds

Sample Questions: Short Answer

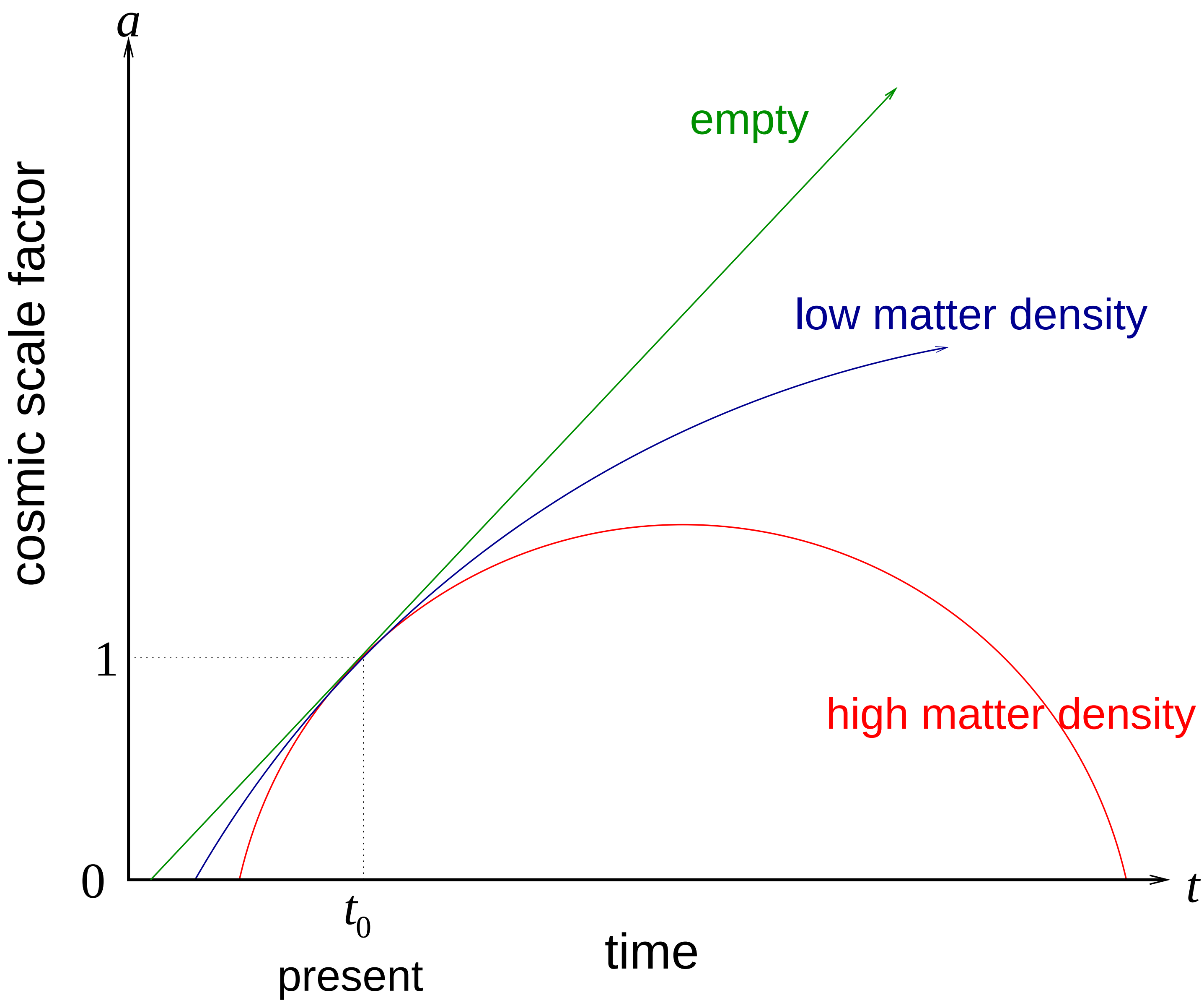
The plot below shows the cosmic scale factor versus time for three different universes



Clearly label which of these is

- an “empty” universe
- a universe with a low matter density
- a universe with a high matter density

For each of these universes, state the final fate.


a
cosmic scale factor
empty
low matter density
high matter density
1
0
t
t_0
present
time

Sample Questions: Short Answer

The Principle of Relativity

(a) What is the Principle of Relativity? Explain in 1-2 sentences.

(b) Give one example of an effect that is a consequence of this principle.

Black holes, dark matter, and gravitational lensing.

(a) Give two properties of black holes that make them good dark matter candidates.

(b) Briefly explain what is gravitational lensing?

(c) Briefly explain how can we use gravitational lensing to detect black holes in our Galaxy's halo.